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HOLPA-based multidimensional assessment for context-specific agroecological transitions in semi-arid Tunisia

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Agroecological transitions offer a viable pathway for transforming agri-food systems toward sustainability, yet fostering durable adoption and meaningful impact requires a deep understanding of local socio-ecological contexts to design targeted, context-sensitive interventions. This study aims to characterize the socio-ecological context, adherence to agroecological principles, and multi-domain performance to identify leverage points for strengthening system resilience. We applied the Holistic Localized Performance Assessment (HOLPA) framework in six rural communities (167 farm households) in the semi-arid Kef–Siliana transect (Tunisia), combining household surveys, soil sampling, contextual diagnostics, scoring of adherences to agroecological principles, and performance indicators (agronomic, environmental, social, and economic). Results reveal pronounced heterogeneity across the studied communities, with distinct degrees of agroecological integration reflecting divergent biophysical conditions, resource endowments, and institutional contexts. Overall, Tunisian rural communities appear to be engaged in an incipient yet uneven agroecological transition. A consistent duality characterizes this process: Social values, including fairness and equity, and some recycling practices are relatively well established, whereas ecological functionality (soil health, ecological synergies), knowledge co-creation, and climate-mitigation practices remain weak. This heterogeneity underscores that agroecological transitions are highly context-specific processes shaped by local assets and governance environments, rather than uniform or linear pathways. Performance patterns highlight the interplay between diversification and resilience: more diversified systems exhibited lower crop losses, while simplified systems (monoculture-dominated systems) suffered greater agronomic and environmental vulnerability. Our application reveals that HOLPA's current household-level and static design constrains the analysis of temporal dynamics and landscape-scale interactions; capturing the full complexity of transitions will require future iterations to integrate longitudinal and spatial monitoring. Nonetheless, this study

demonstrates that HOLPA proves effective in integrating farm household-level diagnostics with system-level performance, offering structured guidance for developing localized roadmaps that highlight context-specific entry points and potential pathways to co-design resilient, equitable, and context-sensitive agri-food systems.

KEYWORDS

agroecology, local indicators, performance assessment, small holder farming, sustainable agri-food systems

1 Introduction

Climate change, land degradation, and biodiversity loss threaten food production in semi-arid regions like North Africa, where most cultivated land faces drought and erratic rainfall (Nguyen et al., 2023). This exposes the limits of input-dependent farming and underscores the imperative to build climate-resilient agri-food systems. These multiple challenges reveal the structural limits of input-dependent farming systems that prioritize short-term productivity at the expense of long-term resilience (Bailey and Buck, 2016). Building climate-resilient agri-food systems that sustain both people and ecosystems has thus become a central policy and research imperative (Bezner Kerr et al., 2021; Campos et al., 2021).

Agroecology has emerged as both a scientific discipline and a practical movement to redesign agricultural systems for sustainability, resilience, and equity. Initially centered on ecological processes within crop production, agroecology has expanded into a multidimensional paradigm encompassing environmental, social, and economic dimensions of food systems (Gliessman, 2018; Wezel et al., 2020). As a science, it studies the interactions between plants, animals, humans, and the environment to optimize ecological functions such as nutrient cycling, pest regulation, and biodiversity conservation (Gliessman, 1990). As a set of practices, it minimizes external synthetic inputs and relies instead on ecological processes and synergies within agroecosystems (Wezel et al., 2020). Beyond science and practice, agroecology also represents a social and political movement that advocates for food sovereignty, farmers rights, and local autonomy in food systems (Frison and Clément, 2020). It promotes short supply chains, fair markets, and the recognition of traditional knowledge and cultural identity as drivers of sustainability (Boutagayout et al., 2023). This integration of ecological, socio-economic, and governance dimensions positions agroecology as a transformative framework rather than a management practices, a paradigm capable of addressing both the biophysical and social drivers of agri-food system vulnerability (Dumont et al., 2016; Gliessman, 2018). Assessing how transitions progress and perform across contexts is key to building evidence and supporting these transitions.

However, many existing assessment approaches, based on conventional productivity or economic efficiency metrics, fail to capture the multidimensional nature of agroecological performance (Darmaun et al., 2023). While yield remains an important indicator, it provides an incomplete representation of sustainability when

detached from ecological integrity, social equity, and local resilience. To fill this gap, various assessment frameworks have been developed over the past decade. Among them, the FAO's Tool for Agroecology Performance Evaluation (TAPE) offers a standardized global methodology for tracking progress based on the 10 FAO agroecological elements (Mottet et al., 2020). TAPE has improved data comparability across regions but often struggles to capture local specificities that determine transition dynamics. Its largely top-down structure can miss the participatory and place-based dimensions essential to agroecology, particularly in heterogeneous smallholder systems (Geck et al., 2023). Similarly, other farm-level frameworks like the Original Agroecological Survey and Indicator System (OASIS) tool (Wezel et al., 2025), designed to assess a farm's position on an agroecological transition trajectory across five dimensions, and territory-level tools like the monitoring tool for Eco-Regions based on Porter's Diamond model (Zanasi et al., 2020), emphasize multi-dimensional indicators but may require adaptation for highly context-specific, semi-arid socio-ecological systems.

Empirical applications of TAPE and similar standardized tools also underline the challenges of fully capturing locally specific practices, priorities, and transition pathways, particularly in heterogeneous smallholder and semi-arid systems (e.g., Ameur and Leauthaud, 2025). These studies point to the need for complementary approaches that allow greater flexibility in indicator selection and interpretation while preserving analytical coherence.

Given the context-dependence of agroecology, there is growing recognition of the need for tools that combine global coherence with local adaptability. Such tools must capture the biophysical, economic, and social dimensions of farming systems while also engaging local actors in indicator selection and interpretation (Jones et al., 2024). The shift from prescriptive frameworks to participatory and context-sensitive assessments is now seen as central to operationalizing agroecology as both science and practice (Darmaun et al., 2023; Cartagena et al., 2025). The Holistic Localized Performance Assessment (HOLPA) framework was developed within the CGIAR Transformative Agroecology Initiative to address these methodological and operational challenges (Jones et al., 2024). HOLPA integrates three analytical modules: Contextual analysis, characterizing the biophysical, socio-economic, and institutional conditions shaping farming systems; Adherence to agroecological principles, evaluating how closely household practices align with the 13 principles of agroecology; and Performance assessment, measuring outcomes across

agronomic, environmental, economic, and social dimensions. While existing agroecological assessment tools have contributed substantially to structuring evaluation efforts, many remain limited either by a strong reliance on predefined indicators or by a partial integration of principles and performance outcomes. The HOLPA framework advances the methodological landscape by introducing an integrated analytical architecture that combines contextual diagnostics, adherence to agroecological principles, and multidimensional performance assessment within a single framework.

A key innovation of HOLPA lies in its explicit linkage between household-level adherence to agroecological principles and observed agronomic, environmental, economic, and social performance outcomes, enabling a diagnostic rather than purely descriptive evaluation of agroecological transitions. In addition, HOLPA operationalizes a Local Indicator Selection Process (LISP), through which indicators are locally adapted and weighted according to context-specific priorities, while preserving analytical coherence and comparability across sites.

By operating at the household scale, where most management and innovation decisions are made, HOLPA provides a fine-grained and context-sensitive assessment of agroecological transitions, thereby complementing and extending existing evaluation frameworks.

The framework is implemented through household surveys, expert assessments, and participatory workshops, ensuring both scientific rigor and stakeholder ownership (Jones et al., 2024). Its Local Indicator Selection Process (LISP) allows each site to adapt and weight indicators according to locally relevant sustainability challenges while maintaining comparability across countries. In contrast to top-down tools, HOLPA focuses on the household scale, the level at which most management, labor, and innovation decisions occur, thus offering a fine-grained understanding of how agroecological transitions manifest in practice. By linking adherence to agroecological principles with actual performance outcomes, HOLPA moves beyond static description toward a diagnostic approach that identifies leverage points for improvement. This capacity to connect principles and outcomes provides actionable insights for policy, extension, and community-based adaptation strategies.

In Tunisia, previous Tunisian studies have assessed agroecological performance and transitions, but mostly through specific tools or single-entry approaches. For instance, Gharbi et al. (2025) applied the TAPE framework in central Tunisia to assess farm-level adherence to agroecological principles and performance, offering structured but largely plot- and farm-based insights. Souissi et al. (2024) used a socioeconomic survey approach linking farmers' perceptions and management decisions to agroecological change, focusing mainly on decision-making dynamics at the household level. Schütze et al. (2025) explored soil governance analysis as an entry point to understand enabling conditions for agroecological practices. Mejri et al. (2025) examined value-chain analysis in the olive sector to highlight how market dynamics shape smallholder transitions (Ameur and Leauthaud, 2025). used the Farm-Level Agroecology Criteria Tool (F-ACT) to assess mainly the alignment with agroecological principles. Frija et al. (2025) used a political economy framework to

investigate the dynamics of pastoralist systems in semi-arid Tunisia, pointing to structural constraints and opportunities.

While these studies have generated valuable evidence, they remain fragmented each focusing on a particular entry point. Without multidimensional assessment, policies and interventions risk being generic, failing to reflect the multifunctional realities and priorities of smallholder farmers in semi-arid regions, and overlooking their potential contributions to broader food system transformation and the Sustainable Development Goals. To fill this gap, the present study applies the HOLPA framework adapted to Tunisia context, focusing on the Kef–Siliana transect, a region emblematic of smallholder mixed systems in semi-arid. We analyze the strengths, weaknesses, and opportunities of local agri-food systems across six rural communities. Specifically, this study aims to (1) assess contextual drivers and constraints, (2) evaluate adherence to agroecological principles, and (3) analyze multidimensional performance to identify leverage points for strengthening system resilience. By integrating these dimensions, this study provides an evidence-based understanding of how agroecological transitions progress in practice, where they advance, where they stand, and why.

2 Methodology

2.1 Study area

The study was conducted in six rural communities of the Kef–Siliana transect in northwestern Tunisia: Kesra, Chouarnia, Elles, Sers, Rhahla, and Hammam Biadha (Figure 1). Recognized as a priority zone by the Agroecology Initiative (Alary et al., 2023), this transect represents a semi-arid Mediterranean environment, with mean annual rainfall ranging from 350 to 550 mm and pronounced inter-annual variability. Average temperatures range between 3–35 °C in Siliana and 7–27 °C in Kef. Farming systems are dominated by smallholder mixed cereal–tree–livestock, with more than two-thirds of holdings smaller than 5 ha (Marzin et al., 2016). The region faces structural constraints including land fragmentation, soil erosion, recurrent droughts, and high rates of poverty and out-migration. Despite these challenges, agricultural diversity persists through cereals, olives, small ruminants, and agroforestry systems (Attiaoui and Boufateh, 2019).

2.2 HOLPA framework and local adaptation

Agroecological performance was assessed using the Holistic Localized Performance Assessment (HOLPA) framework (Jones et al., 2024), which integrates three modules. The Context module characterizes socio-demographic, institutional, and biophysical conditions shaping farm management, including household composition, land tenure, farm size, and market access, drawing on RHoMIS indicators where relevant (Hammond et al., 2017). The Agroecology adherence module operationalizes the 13 HLPE principles (Nicolétis et al., 2019), each represented by at least one locally relevant item scored on a five-point Likert scale (1 = minimal

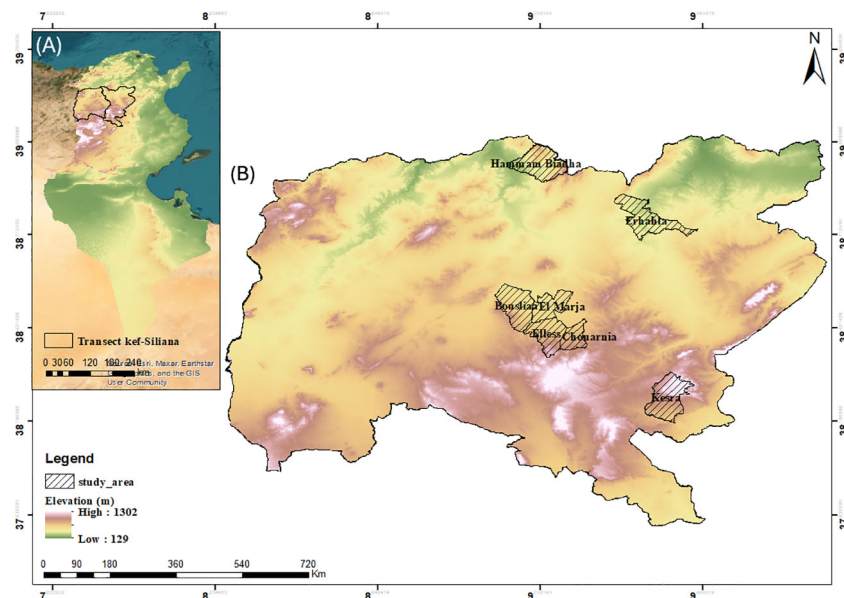


FIGURE 1

Location of the Kef–Siliana transect in northwestern Tunisia. (A) the location of Le Kef and Siliana governorates; (B) a zoomed view of the transect, highlighting the six study communities.

alignment; 5 = strong alignment) and standardized to [0–1] (Supplementary Table 1). The Performance module comprises 18 indicators grouped into four domains (Agronomic, Environmental, Economic, and Social) covering yield loss, animal health, soil organic carbon, nutrient management, biodiversity, use of local varieties and breeds, water stress, household income, dietary diversity, life satisfaction, and land tenure security.

HOLPA was adapted to the Tunisian context through a Local Indicator Selection Process (LISP). A participatory workshop involving 15 local farmers and 10 national experts (agronomists, socio-economists) refined the indicator set to capture context-specific features, such as local food groups and tree or livestock diversity, while ensuring consistency and comparability with global metrics. Participants reviewed and refined the indicator set to ensure local relevance, with consensus reached through facilitated discussion. Survey items and field measurements were mapped to Key Performance Indicators (KPIs) to enable subsequent farm-level assessment (Supplementary Table 2).

2.3 Survey design and sampling

Data collection was conducted in two phases. The first phase involved a household survey of 167 farms using structured digital questionnaires. Eligible households engaged in crop and/or livestock production, with at least 25% female respondents per community. Enumerators were trained in survey logic, digital data entry, and ethical procedures. In the second phase, a sub-sample of 77 farms was selected from the household survey. The selection used a stratified random approach based on Socio-Ecological Context Types (SECTs) (Shiri and Le, 2024) to ensure this sub-sample represented the full range of biophysical and socio-economic diversities present across the transect. Data was

recorded on tablets using ODK/KoboCollect. Soil samples (0–20 cm) were analyzed for organic carbon using dry combustion.

2.4 Data processing and analysis

All data were processed and analyzed using R v4.2.2 (R Development Core Team, 2022). The workflow comprised four sequential steps. First, raw survey and field data were cleaned and harmonized, including translation of open responses, unit standardization, correction of inconsistent household identifiers, and verification of geographic coordinates, using the tidyverse suite (dplyr, tidyr, stringr) (Wickham et al., 2019). Second, survey responses and field measurements were transformed into standardized indicators (psych, DescTools) (Revelle, 2025; Signorelli, 2025). Continuous variables (e.g., soil organic carbon, livestock mortality, dietary diversity) were normalized using min-max scaling (scales), and binary indicators (e.g., use of local varieties) were coded directly as 0–1. Scoring and aggregation were performed at the farm level. Agroecology adherence was calculated as the median of standardized principle scores, and performance indicators were aggregated into the four domains (Agronomic, Environmental, Economic, Social). The median was selected because Likert-scale data are ordinal rather than continuous, and because the median provides a robust measure of central tendency that is less sensitive to extreme or divergent responses across practices within a household. Missing values $\leq 20\%$ per indicator were imputed, while indicators with $>20\%$ missing were excluded. Aggregation procedures were implemented using the dplyr package for data manipulation (Wickham et al., 2014) and the purrr package for functional programming, which was particularly useful for applying operations across nested data structures (Wickham and Henry, 2025). Finally, statistical analysis

included descriptive statistics reported as mean $\pm$ SD and median with interquartile range (IQR).

3 Results

3.1 Context assessment

Marked differences in household demographics, livelihood strategies, perceived environmental risks, and service access characterize the six study communities (Tables 1, 2). Household heads are predominantly older than 35 years (77 to 100%), with Kesra showing the largest share of younger heads (23%). Household labor composition is relatively balanced by gender, though men represent a higher proportion of active members in Kesra, Rhahla, and Sers, while women are more represented in Elles.

Education levels vary substantially. Illiteracy is most prevalent in Elles (29%) and Hammam Biadha (27%), whereas Kesra records the highest proportion of household heads with higher education (19%). Primary and secondary schooling dominate in all sites, ranging from 57% in Elles to 82% in Rhahla. Livelihoods are largely based on mixed crop–livestock systems, reported by 63–97% of households. Exclusive crop production is more frequent in Hammam Biadha (26%) and Kesra (31%), while income diversification beyond agriculture remains marginal across all sites (<6%). Access to services and infrastructure reveals strong spatial disparities. Hammam Biadha is the most isolated community, with households reporting distances of 48 km to the nearest hospital and 50 km to markets. In contrast, Elles and Chouarnia benefit from close proximity to schools and health facilities (<5 km). Kesra occupies an intermediate position, with short distances to schools and water sources but longer access to markets (7.5 km). Public transport is generally available across all sites (Table 1). Perceptions of environmental constraints further differentiate communities. Cultivation on moderately steep terrain is widespread in Hammam Biadha (42%), Chouarnia (42%), and Rhahla (58%), while steep slopes are most frequent in Elles (42%). Soil erosion is perceived as a major problem in Rhahla (20%) and Hammam Biadha (10%), but dismissed by the majority in Elles and Sers (74% each). Soil fertility is generally rated as moderate (61–77%), with highly fertile soils more frequently reported in Kesra (36%) and Hammam Biadha (22%).

Household land and farm composition vary markedly across communities, with Kesra exhibiting the highest tree cover and Chouarnia the largest cereal area, while livestock density is greatest in Elles and Rhahla, reflecting distinct land-use strategies and production intensities (Table 2).

These contrasts illustrate the structural heterogeneity of the transect and provide the basis for interpreting differences in agroecological adherence and performance in subsequent modules.

3.2 Assessment of adherence to agroecological principles

The adherence of farms to the 13 HLPE agroecology principles was evaluated using the HOLPA Agroecology Adherence module.

Principles were grouped into three priorities: Improving Resource Efficiency, Strengthening Resilience, and Enhancing Social Equity and Inclusion. Scores were recorded on a 5-point Likert scale (1 = minimal adherence, 5 = strong adherence) (Figures 2–4).

Resource Efficiency focuses on optimizing local resources and reducing reliance on external inputs through recycling and input reduction. Recycling, reflecting the closure of nutrient and energy loops, showed moderate adoption across communities (mean = 3.0/5, where a score of 3 indicates basic implementation), with high scores for manure and compost reuse (4–5) and low scores for energy sourcing (1.0), indicating continued reliance on purchased sources. Seed and livestock sourcing were intermediate, with Elles and Sers achieving the highest mean scores (3.1) and Kesra the lowest (1.0). Input Reduction, representing the substitution of synthetic inputs with agroecological alternatives, averaged 2.7 across communities. Soil fertility and pest management scored higher, particularly in Hammam Biadha (3.0), whereas livestock disease management remained weak. Overall, Resource Efficiency practices are partially adopted, with nutrient recycling outperforming input reduction strategies (Figure 2A, 3).

Resilience-enhancing practices include soil health, animal health, biodiversity, ecological synergy, and economic diversification. Soil health scored lowest across the transect (1.0), reflecting limited application of cover cropping, no-till, and crop rotation, with marginally higher adoption in Rhahla. Animal health averaged 3.0, with Sers and Rhahla scoring 3.2, showing moderate implementation of feeding and shelter practices but limited preventive care. Biodiversity scored 2.8, with Kesra highest and Rhahla lowest, reflecting differences in landscape heterogeneity. Ecological synergy remained underdeveloped (1.6), with partial integration such as manure reuse but little systemic linkage among crops, livestock, trees, soil, and water. Economic diversification was low (1.8), as most households relied on a single agricultural activity, constrained by climate and market access. Collectively, resilience practices show moderate adoption in animal health and biodiversity, but critical gaps remain in soil management, system integration, and livelihood diversification (Figures 2B, 3, 4).

Social equity practices, covering knowledge sharing, social values, fairness, connectivity, governance, and participation, revealed heterogeneous adherence. Knowledge sharing was limited (1.6), with Sers and Kesra showing higher engagement through development agencies and agro-tourism networks, while Elles and Hammam Biadha reported minimal interactions. Social values, including access to traditional, seasonal, and healthy foods, scored highest (4.3, 4.0, and 3.8, respectively), reflecting strong cultural and nutritional sustainability. Fairness averaged 3.9, with honey and livestock markets rated positively, but tree-product pricing varied. Connectivity to markets was low for crops (1.0) but higher for honey and livestock (mean = 2.5). Governance and participation showed moderate but variable engagement (2.6–2.7), with Chouarnia and Sers performing better due to established farmer organizations. Overall, social equity practices indicate strong cultural embeddedness and partial market fairness, but knowledge sharing, connectivity, governance, and participation remain limited (Figures 2C, 3, 4).

TABLE 1 Context module: household demographics, livelihoods, environmental perceptions, and access to services across six Tunisian communities.

Section	Modality	Chouarnia	Elles	Hammam Biadha	Kesra	Rhahla	Sers	Total
Household head age	< 35 years (%)	7	0	14	23	14	0	12
	≥ 35 years (%)	93	100	86	77	86	100	89
Household composition	Active household members, Male (%)	50	43	50	55	59	60	55
	Active household members, Female (%)	50	57	45	45	45	45	47
Education level	None (%)	11	29	27	0	14	15	13
	Primary or secondary (%)	79	57	68	81	82	75	75
	Higher (%)	11	14	5	19	5	10	11
Livelihood (income sources)	Crop production only (%)	17	7	26	31	15	3	17
	Crop & livestock production (%)	83	93	70	63	81	97	80
	Other income sources (%)	0	0	4	6	4	0	3
Perceived environmental risks	Slope (terrain), Flat (%)	14	43	15	16	8	42	23
	Slightly steep (%)	25	15	26	18	32	22	23
	Moderately steep (%)	42	0	42	41	58	15	33
	Steep (%)	19	42	17	25	2	21	21
	Soil erosion, Major problem (%)	6	0	10	8	20	0	7.9
	Soil erosion, Minor problem (%)	26	26	16	37	45	30	30
	Soil erosion, not a problem (%)	68	74	74	55	35	70	61
	Soil fertility, highly fertile (%)	16	16	22	36	13	16	20
	Soil fertility, moderately fertile (%)	72	74	67	61	77	76	71
	Soil fertility, Low fertility (%)	12	10	11	3	10	8	8
Access to services & infrastructure	Distance to public hospital (km)	5	5	48	2.5	11	5	–
	Distance to market (km)	12	8	50	7.5	16	7	–
	Distance to water source (km)	0.2	0.8	3.8	0.1	6	1.2	–
	Distance to primary school (km)	2.2	1.7	1.9	2	4.3	3	–
	Distance to public transport (km)	0.4	0.6	0.4	0.6	0.7	1	–
	Suitable road for car (km)	0.9	0.6	1.5	0.6	1.1	1.1	–

TABLE 2 Household land, crop, and livestock profiles across six communities (n=167).

	Chouarnia	Elles	Hammam Biadha	Kesra	Rhahla	Sers	Overall total
Land owned (ha)	12.6	5.2	5.5	8.6	9.1	5	10.2
Tree (Olive, Fig in ha)	1	0.3	1.5	4.4	0.7	0.2	1.6
Cereal (ha)	9.1	2.3	1.1	1.5	6.1	1.6	4
Cattle (nb)	4.8	2.6	1.5	1.1	1	1.9	2.1
Sheep (nb)	31.6	27.1	11.7	24.8	44	20.4	26.6
Goats (nb)	1.6	0	0.1	2.6	1	1.5	1.3
Livestock by land (nb/ha)	3	5.7	2.4	3.3	5.1	4.8	2.9

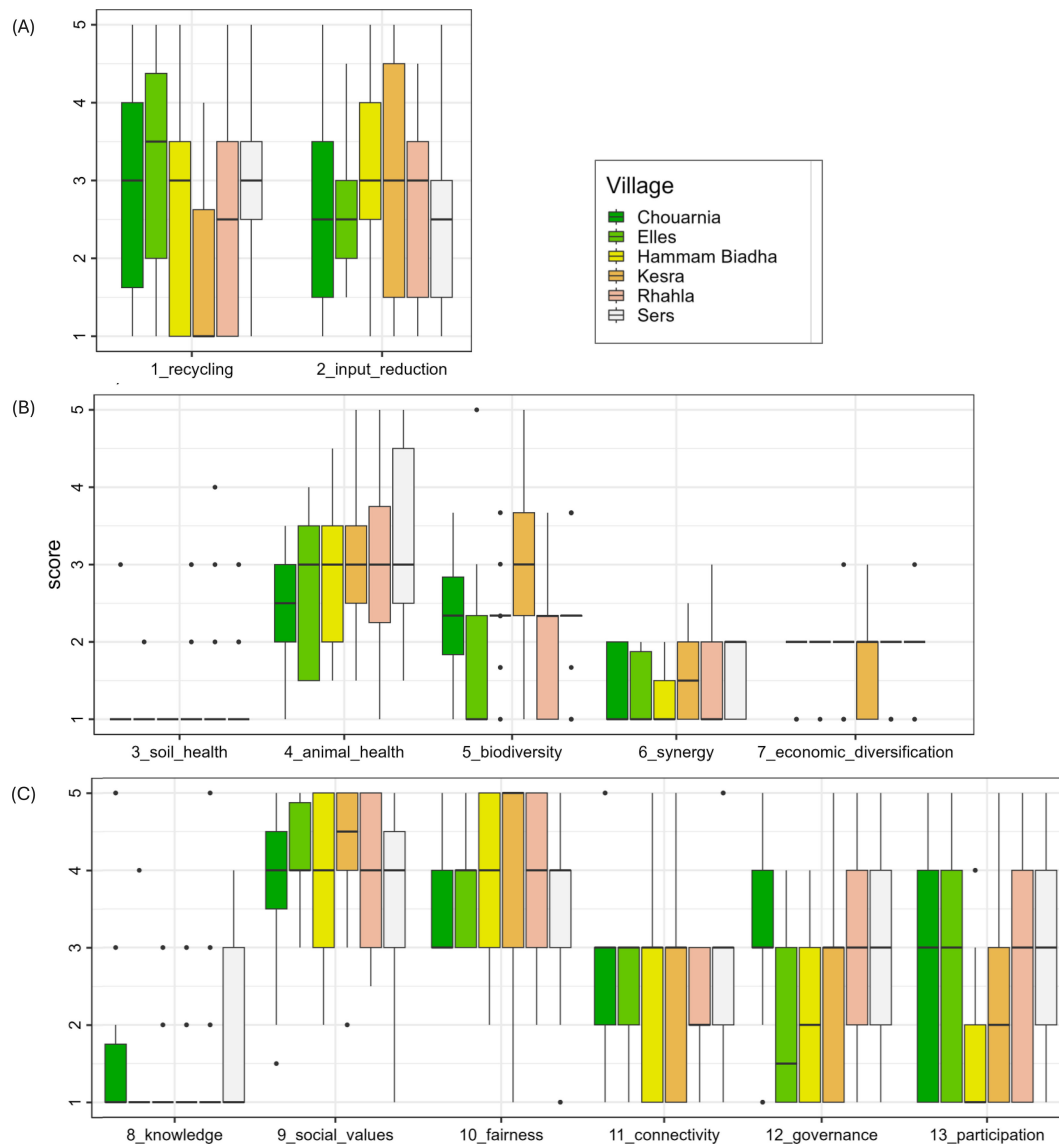


FIGURE 2
Community-level scores of the 13 agroecology principles (Agroecology Adherence module) grouped into “Improve Resource Efficiency” (A), “Strengthen Resilience” (B), and “Secure Social Equity” (C) across the six Siliana–Kef transect communities. Scores range from 1 to 5, reflecting adherence to each principle in each community.

Overall agroecology adherence across the 13 principles varied both within and between communities (Figure 4). Practices related to nutrient recycling and social values consistently received higher scores, whereas soil health, ecological synergy, and knowledge sharing were among the lowest, indicating persistent gaps in holistic adoption.

3.3 Performance assessment

The performance assessment across the Kef–Siliana transect revealed marked contrasts between agronomic, environmental, social, and economic dimensions (Figures 5, 6).

Agronomic indicators (KPI1 to KPI3) highlight the vulnerability of production systems to multiple stresses (Figure 5A). Crop Health indicator (KPI1) was assessed based on the percentage of

total crop production lost or damaged in the past 12 months. Lower scores indicate lower levels of crop loss or damage, while higher scores reflect a higher incidence of crop production losses. The overall average score across communities was 3.32, indicating moderate to high levels of crop vulnerability in the region. Chouarnia (3.98) and Rhahla (3.79) recorded the highest levels of crop loss, which may reflect greater exposure to climatic variability, pest pressure, or insufficient protective practices. In contrast, Kesra reported the lowest crop loss score (2.19), suggesting relatively limited production damage and a more resilient cropping system. Livestock health indicator (KPI2), measured by the extent of livestock illness, injury, or mortality due to disease over the past 12 months, presented the most critical constraint, with a transect mean of 4.0. Chouarnia (4.25) and Kesra (4.24) had the highest livestock health scores, reflecting widespread incidence of disease and mortality. Hammam

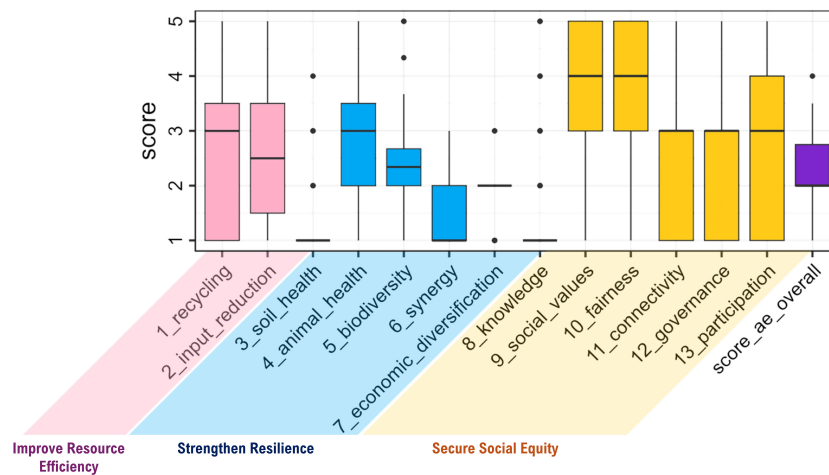


FIGURE 3

Across communities scores of the 13 agroecology principles (Agroecology Adherence module across the six Siliana–Kef transect. Scores range from 1 to 5, reflecting adherence to each principle.

Biadha and Elles showed relatively better livestock health conditions, likely reflecting more effective disease management practices or better veterinary access. For soil health indicator (KPI13), which was inversely scored so that higher values indicate poorer soil conditions (i.e., more infertile soil with significant erosion), higher scores were reported in Sers (4.51) and Elles (4.33). Rhahla recorded the lowest score (3.37), reflecting relatively less severe degradation. These results underline the coexistence of soil decline with uneven crop and livestock resilience across the transect.

Environmental performance (KPI5 to KPI9) revealed both strengths and weaknesses (Figure 5B). Animal diversity (KPI5a) averaged 3.1 and ranged from 2.8 in Sers to 3.6 in Kesra, where mixed-livestock systems remain stronger. Tree diversity (KPI5b) revealed marked differences. Kesra's score of 3.8 reflects widespread

agroforestry integration, while Elles, with only 1.7, showed minimal perennial cover and limited ecological buffering. Genetic diversity indicator (KPI6b) was measured through the use of local varieties and breeds. The average score across the sites was 3.39, indicating a generally positive trend in the conservation and use of locally adapted genetic resources. The highest levels were reported in Sers and Rhahla (scores of 3.45 and 3.55, respectively), suggesting a strong reliance on locally adapted varieties and breeds. The climate mitigation indicator (KPI8), which captures the extent to which farms apply practices enhancing carbon sequestration, showed relatively weak performance (averaged 2.41). The highest score was observed in Hammam Biadha (2.85), likely due to partial adoption of organic inputs or reduced tillage. By contrast, the avoided water stress indicator (KPI9), expressed as the proportion of months without significant irrigation deficits, recorded the most favorable results. The overall mean score was 3.89, indicating some resilience to seasonal water shortages even in this semi-arid context. Sers and Rhahla reported the highest values (4.12 and 4.05, respectively), which may be attributed to better water resource management or the cultivation of drought-resilient crop varieties.

Social indicators (KPI15 to KPI18) provide insights into the tenure stability, food access, and overall quality of life of farming households across the six surveyed communities. Dietary diversity indicator (KPI15) reveals a relatively low overall score across the transect, with an average of 3.54. The highest diversity score was observed in Kesra (3.89), potentially linked to diversified production systems and agroecological conditions favorable to varied food production. Conversely, Sers (3.27) and Chouarnia (3.28) show the lowest scores, pointing to more limited access to a variety of food groups, possibly due to climatic constraints or limited crop diversification. Land tenure security indicator (KPI17), captured through perceived risk of land loss, demonstrates strong confidence across most communities, with an overall average score of 4.47 (Figure 5C). Hammam Biadha (4.84), Sers (4.68), and Rhahla (4.68) report the highest levels of perceived security, reflecting relatively stable land access. Similarly, the ownership share of household land (KPI17b) is consistently high, averaging 4.35, with the highest ownership proportions found in Elles (4.56) and Kesra (4.55).

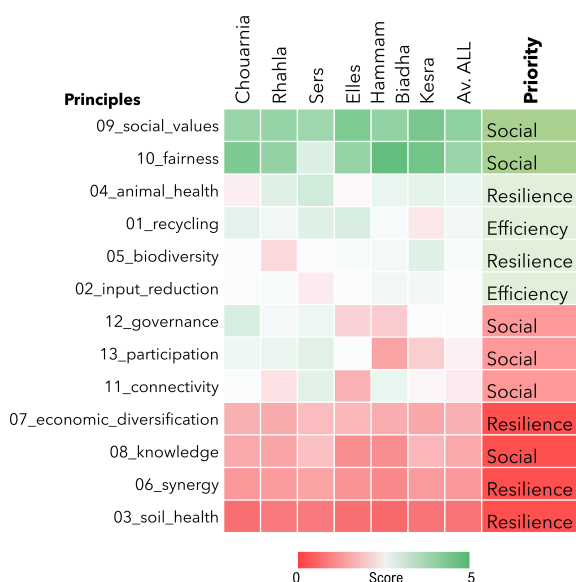


FIGURE 4

Heat map of average scores for the 13 agroecology principles (Agroecology Adherence module) across the six Siliana–Kef transect communities. Principles are ordered from lowest to highest average score.

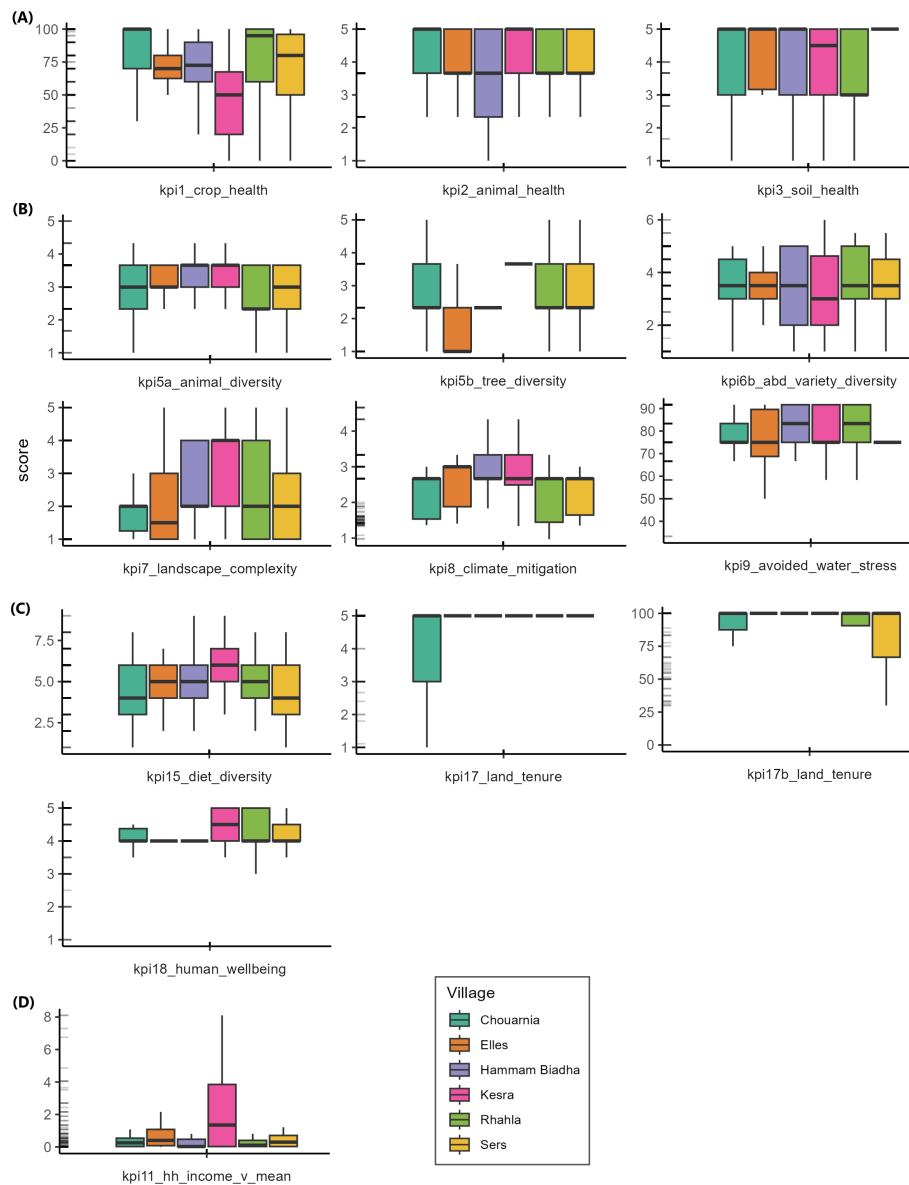


FIGURE 5

Performance assessment of farming households across six communities in the Kef–Siliana transect, based on 13 Key Performance Indicators (KPIs). Box plots show variation across four dimensions: (A) Agronomic, (B) Environmental, (C) Social, and (D) Economic performance.

These findings suggest that most respondents operate under secure and autonomous land tenure arrangements, which may facilitate long-term investment in sustainable land management. In terms of human well-being (KPI18), as measured by perceived life satisfaction, the average score is 3.94, reflecting a generally positive outlook across communities.

Economic performance, captured by household income relative to the national mean (KPI11), revealed a high disparity (Figure 5D). Kesra households averaged 2.1, more than double the national reference, while Elles remained above average (1.4). By contrast, Chouarnia (0.9) and Sers (0.9) fell well below parity, highlighting stark income inequalities within the transect.

Together, the 14 KPIs depict fragmented trajectories of agroecological transition. Kesra consistently combined lower crop losses, stronger biodiversity, and higher incomes, while Chouarnia and Sers clustered multiple vulnerabilities across production,

environment, and livelihoods. These contrasts highlight the need for site-specific pathways to strengthen agroecological transition.

4 Discussion

This study represents the first comprehensive application of the HOLPA framework in Tunisia. By integrating a contextual module, an agroecological adherence module, and a multi-domain performance module, HOLPA offers a holistic understanding of where agroecological transitions are progressing, their current status, and the factors driving them. Two main key findings emerge: 1. The degree of species and varieties' diversification in the mixed crop-tree-livestock systems between the communities is partly explained by the contextual heterogeneity (infrastructure,

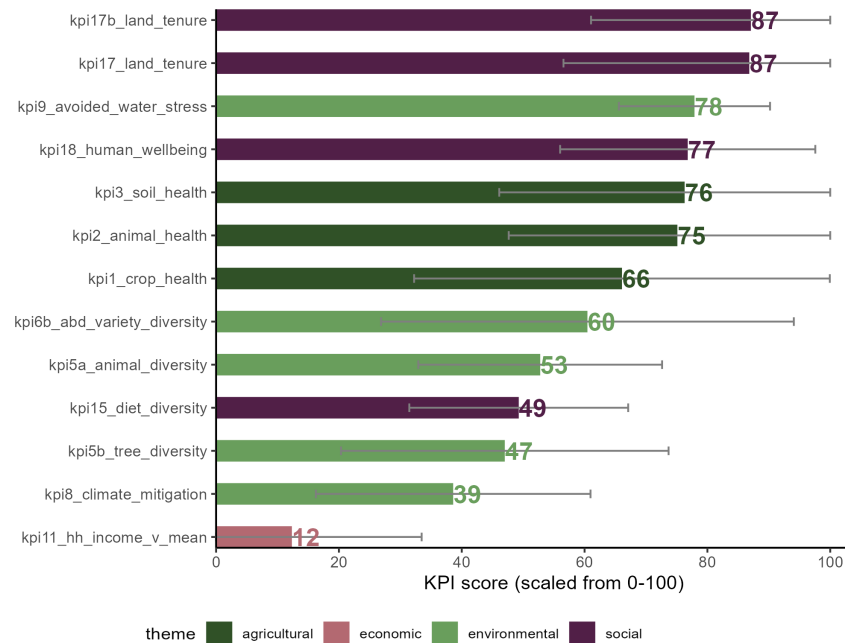


FIGURE 6

Mean performance scores across the six communities: KPI ranked from highest to lowest.

institutional support) and it highly conditions the agroecological performance in term of ecological functioning and the adaptive capacity to shocks; and, 2. When social capital remains largely inward-looking and community-bound, it often reinforces individual and collective coordination mechanisms at a low scale without connecting them to the technical, ecological, and multi-scale institutional capacities required to manage natural resources sustainably. In such cases, individual motivation and collective cohesion may be high, yet ecological outcomes remain weak because social capital is not articulated across scales nor translated into adaptive rules, knowledge systems, and governance arrangements that enable ecological performance and long-term development. Beyond revealing these patterns, the study demonstrates both the operational value and limitations of HOLPA as a field-ready framework capable of linking household-level realities to system-level transitions.

4.1 Contextual drivers and constraints

While farming systems across the transect are predominantly mixed, the degree of crop-livestock-tree integration varies considerably among communities. In Kesra, the integration of cereals, olives, and small ruminants supports higher biodiversity and resilience, while Elles and Hammam Biadha remain constrained by cereal or olive-based monocultures. Such structural contrasts shape the adoption and effectiveness of agroecological practices, particularly those relying on functional biodiversity and landscape-level interactions. System diversification is a central determinant of agroecological performance, as greater crop and livestock diversity supports multiple ecosystem services, including nutrient cycling, pest regulation, and climate buffering (Leclère et al., 2014; Gawdiya et al., 2025). More diversified systems also enhance farm-level resilience and offer broader livelihood

options, which are especially critical in dryland contexts (Wezel et al., 2020; Vernooij, 2022). The lower diversification observed in Elles and Hammam Biadha likely constrains their adaptive capacity, whereas promoting the reintegration of livestock, leguminous crops, and agroforestry could reinforce ecological functionality and long-term sustainability.

Spatial disparities in access to services and infrastructure further shape farmers' capacity to engage in agroecological transitions. Remote communities, such as Hammam Biadha and Rhahla, face isolation that restricts innovation diffusion. The absence of institutional presence in these areas amplifies social and economic inequalities, limiting opportunities for co-designing locally relevant solutions (Anderson et al., 2021). Bridging these infrastructural and service gaps is therefore essential for ensuring equitable access to knowledge, financial resources, and institutional support, which constitute the foundational drivers of agroecological transformation.

Socio-demographic variables, particularly age, education, and household structure, interact with these spatial and structural factors to shape the capacity for innovation and adoption. The association between younger, better-educated households and higher biodiversity in Kesra aligns with evidence that human capital facilitates experimentation and uptake of knowledge-intensive practices (Musafiri et al., 2022; Børresen et al., 2023; Gashu et al., 2025). Conversely, aging farming populations, such as in Chouarnia, may face labor shortages and limited openness to change, constraining the sustainability of transition processes. Souissi et al. (2024) confirmed these patterns in Tunisia, reporting a negative correlation between farmers age and the adoption of new practices. Nonetheless, literature remains divided, older farmers often exhibit strong knowledge and risk-management experience that can support innovation under certain institutional conditions (García-Cortijo et al., 2019; Yu et al., 2023; Castellini et al., 2025).

Overall, these contextual disparities emphasize that interventions must be both demographically and geographically targeted rather than universal. Understanding these socio-agronomic dynamics is thus essential for interpreting agroecological outcomes and for designing interventions that are socially grounded, ecologically coherent and context-specific.

4.2 Adherence to agroecological principles: strengths and gaps

HOLPA agroecology adherence module revealed that Tunisian rural communities are in an early but uneven phase of agroecological transition. The principal empirical insight is a consistent duality: social values, fairness and some recycling practices show relative strength, whereas ecological functionality (soil health, ecological synergy), knowledge co-creation and climate-mitigation practices remain weak. This configuration aligns with previous Tunisian and regional studies (Ameur and Leauthaud, 2025; Frija et al., 2025; Gharbi et al., 2025), and it carries implications for how policy, research, and development stakeholders should sequence and target interventions.

Resource efficiency (particularly input reduction through manure use and composting) scored moderately high, consistent with findings from the Merguellil Plain and central Tunisia, where nutrient cycling dominates adoption (Ameur and Leauthaud, 2025). Resilience-enhancing practices, particularly those targeting animal health and biodiversity, achieved moderate adherence across sites, with Kesra scoring higher. This outcome likely reflects the alignment of these practices with existing mixed farming traditions, as well as the presence of a younger, better-educated population with an orientation toward innovation. The central role of livestock in mixed systems, together with the persistence of traditional land-use practices, further supports the maintenance of these resilience dimensions. However, the weak performance in soil health and ecological synergy is a substantive deficit with important implications across the transect. This is particularly due to the dominance of cereal or olive-based monocultures in Rhahla, Elles and Hammam Biadha. Weak soil-health practices reflect both biophysical constraints (erosion, steep slopes, drought) and governance gaps, as soil management policies in Tunisia remain fragmented and poorly integrated into farmer practices (Alary et al., 2023; Schütze et al., 2025). Without integrating cover crops, rotations, no-till, and cross-scale linkages between cropping, livestock, tree systems, the broader ecological resilience of farms remains fragile.

However, our study indicates that social dimensions are the most advanced, particularly social values and fairness, which scored highest across communities. This reflects a strong embeddedness of community solidarity, cultural identity, and perceived equity in local food systems, especially in Hammam Biadha, Elles, and Kesra. Social values, fairness, and perceived tenure security create essential enabling conditions for collective action, trust, and local food sovereignty (Jansen, 2015; Frison and Clément, 2020). However, the low scores in knowledge co-creation indicate that while farmers may value fairness and solidarity, the mechanisms for collective experimentation, participatory research, and farmer-to-farmer

learning are underdeveloped. This aligns with broader critiques that technical interventions often outpace institutional development in Tunisia (Schütze et al., 2025). As Anderson et al. (2021) argue, agroecology's transformative potential depends on the co-production of knowledge, yet current extension services remain top-down and poorly equipped to foster farmer experimentation. Strengthening farmer-to-farmer exchange, local experimentation networks, and horizontal learning is therefore critical for advancing ecological dimensions of agroecology. Social capital alone does not automatically generate ecological outcomes, the translation of solidarity into on-farm practices that rebuild soils, re-establish ecological synergies, or sequester carbon requires functioning knowledge systems, accessible inputs and incentives for labor-intensive practices. This gap—strong social foundations but weak ecological functionality—underlines a central paradox of incipient agroecological transitions in the region. These gaps represent constraints to the transformative potential of agroecological transitions, since agroecology relies on ecological functionality and co-created knowledge systems to build systemic resilience (Cartagena et al., 2025).

Participation, connectivity, and local governance mechanisms display moderate scores overall, but their distribution is highly variable. Communities such as Chouarnia and Rhahla demonstrate relatively stronger capacities for participation and governance, whereas Hammam Biadha and Elles perform noticeably lower. This heterogeneity highlights the fragmented nature of governance arrangements in rural Tunisia, where local histories, social capital, and access to services shape collective action in divergent ways. Within the HOLPA framework, these dimensions correspond to the enabling conditions that allow agroecological transitions to consolidate (Wezel et al., 2020). In contexts where governance mechanisms are weak or poorly articulated, pathways toward agroecological resilience risk remaining isolated, localized, and unable to scale. Recent research on polycentric governance in the MENA region further emphasizes that the integration of multiple actors and institutions provides a critical lever for agroecological transformations, yet these arrangements are often underdeveloped in Tunisia (Goetz et al., 2024; Schütze et al., 2025).

Taken together, this consistent duality—advanced social dimensions alongside underdeveloped ecological functionality—presents both a central paradox and a strategic opportunity for Tunisia's agroecological transition. The risk is that strong social cohesion, as seen in communities like Hammam Biadha and Elles, may form resilient social 'bubbles' that remain ecologically vulnerable, ultimately undermining long-term food system sustainability. The opportunity, however, lies in leveraging this robust social foundation—comprising trust, fairness, and tenure security—as a primary entry point for change. The critical task is to activate mechanisms that translate social capital into ecological action. The low scores in knowledge co-creation indicate that the current top-down extension model is insufficient for this task. Therefore, strengthening farmer-to-farmer exchange, establishing local experimentation plots, and fostering polycentric knowledge platforms become paramount. These mechanisms can channel existing community solidarity into the co-creation and adoption of practices that rebuild soil health (e.g., cover crops, compost

application) and restore ecological synergies, effectively using social readiness as a lever to bridge the largest ecological gaps.

4.3 Performance outcomes: uneven resilience and emerging opportunities

Performance outcomes revealed marked contrasts across agronomic, environmental, economic, and social dimensions, allowing an integrated understanding of how agroecological transitions shape system performance.

Agronomic performance, particularly crop and livestock health, reflects the combined influence of system diversification, management intensity, and contextual stressors. During the 2022–2023 agricultural season, marked by low rainfall and high temperatures, communities showed clear differences in resilience. Kesra experienced moderate crop losses (50%), suggesting that diversified land-use mosaics and better ecological management mitigated the impacts of climatic stress. These findings support evidence that diversified systems enhance resilience through resource recycling and risk dispersion (Atapattu et al., 2024). In contrast, Chouarnia faced severe losses (90%), highlighting the vulnerability of monoculture-based systems. Such low ecological integration compromises soil structure and pest regulation, leading to yield instability under climatic stress (Wezel et al., 2020; Vernooij, 2022). The divergence observed between Kesra and Chouarnia thus underscores that agroecological resilience emerges from the interaction of ecological diversification, adaptive knowledge, and institutional support rather than from biophysical conditions alone (Amoak et al., 2022; Dagunga et al., 2023).

Livestock health emerged as another factor affecting the system resilience. High disease incidence and mortality were observed, particularly in Chouarnia and Kesra, reflecting weaker disease management practices or limited access to veterinary services. The duality in Kesra (crop health vs livestock health) underscores a central principle: system resilience depends not only on ecological diversification but also on institutional capacity and adaptive management across components (Day et al., 2025). These contrasts underscore that agroecological resilience emerges from the interplay of ecological diversification, adaptive knowledge, and institutional support, rather than from biophysical conditions alone (Amoak et al., 2022; Dagunga et al., 2023).

Environmental performance exhibits clear spatial gradients, with Kesra consistently scoring higher in animal and tree diversity, reflecting more complex and integrated agroecosystems. These patterns suggest that local actors either intentionally or historically maintain diversified systems that support agroecological principles such as biodiversity and functional synergy. In contrast, climate-mitigation practices remain weak across all communities, with limited adoption of carbon-sequestering measures such as cover cropping, agroforestry, or organic soil amendments, approaches previously shown to enhance resilience in comparable Tunisian systems (Triberti et al., 2016; Ferchichi et al., 2023; Cheikh M'hamed et al., 2025). Observed low soil health scores align with studies highlighting fragmented soil governance and weak farmer engagement as major barriers to sustainable fertility management in Tunisia (Schütze et al., 2025).

By contrast, relatively high scores for the water-stress indicator in several communities indicate that adaptive water-management strategies, including rainwater harvesting, crop selection, and irrigation timing, are effectively implemented despite semi-arid conditions (Sawassi et al., 2024).

On the economic dimension, pronounced disparities emerge. Kesra and Elles report relatively favorable outcomes, likely linked to diversified income sources (e.g., olive production, livestock) and better market integration. Diversified farming systems provide multiple sources of income, making farmers less vulnerable to market fluctuations and price shocks (Rosa-Schleich et al., 2019; Dhehibi et al., 2023).

Social performance indicators show relatively strong outcomes in tenure security and perceived well-being, which are essential preconditions for long-term investment in sustainable practices. Nevertheless, dietary diversity remains a persistent gap, especially in Chouarnia and Sers, suggesting a disconnect between production systems and nutrition-sensitive agriculture. This reinforces the need to promote diversified cropping systems, agroforestry, and local food value chains that enhance the availability of nutrient-rich foods. More broadly, Tunisian and regional assessments stress that agroecological transitions are strongly shaped by social organization and governance: while community solidarity and cultural identity remain assets, weak farmer participation in collective organizations and fragmented institutional support slow down systemic change (Carpentier, 2025; Sghaier et al., 2025).

Overall, HOLPA results in the present study illustrate a partial agroecological transition across the study area, with strengths in social indicators and certain ecological practices, but persistent weaknesses in areas, such as soil health, animal health, and climate mitigation. Addressing these limitations requires a multi-dimensional approach that strengthens farmer capacities, improves access to technical and financial services, and promotes policies tailored to local ecological and socio-economic realities. This integrated perspective highlights the interdependence of ecological management, adaptive knowledge, and governance in shaping agroecological outcomes (Atapattu et al., 2024; Frija et al., 2025).

4.4 Strategic and methodological considerations for context-specific agroecological transitions

A central policy question, therefore, becomes: how to convert local strengths and social capital into ecological transformation at scale? The diagnostic nature of HOLPA allows the translation of observed weaknesses into prioritized interventions. To address the critical gap in soil health (KPI3), which showed high degradation scores (e.g., 4.51 in Sers), targeted soil restoration in erosion hotspots and the integration of leguminous crops to rebuild fertility should be prioritized. The relative strength in nutrient recycling (a component of Resource Efficiency principles) indicates a foundation for promoting composting and organic nutrient management where manure use is already established. The severe constraint of livestock health (KPI2), with a transect mean score of 4.0 indicating high mortality, underscores that

investments in preventive veterinary care and integrated feed systems are not only animal welfare priorities but essential for securing the nutrient cycling pillar of agroecological systems. Furthermore, to overcome the deficit in knowledge co-creation (one of the lowest-scoring principles), interventions must shift from top-down delivery to supporting farmer field schools and on-farm trials, directly engaging the social capital identified as a community strength.

The evidence suggests a multi-dimensional sequence. First, prioritize ecological levers with both high biophysical impact and relative feasibility given labor and knowledge constraints; these include targeted soil restoration in erosion hotspots, integration of legumes to rebuild fertility, and promotion of composting/organic nutrient recycling where manure use is already established (Triberti et al., 2016; Ameur et al., 2020). Second, place knowledge co-creation and farmer-led experimentation at the core of upscaling. Our low scores on knowledge co-creation mirror broader critiques that top-down extension systems fail to deliver contextually adapted agroecology (Cartagena et al., 2025). Strengthening farmer field schools, on-farm trials, and polycentric knowledge platforms that link research institutes, NGOs, and farmer organizations can accelerate localized innovation diffusion (Goetz et al., 2024; Cartagena et al., 2025). Third, address barriers in animal health and veterinary services: high livestock mortality constrains both livelihoods and nutrient cycling (Day et al., 2025). Investments in preventive veterinary care and integrated feed systems are therefore both welfare and agroecological priorities.

Despite its strengths, HOLPA retains some limitations. In its current form, HOLPA provides a static overview of household systems, constraining its ability to capture seasonal variability or long-term change. The current status is highly dependent on the prevailing climate conditions during data collection. Its household-level focus may also overlook interactions occurring at landscape and territorial scales, where many ecological and governance processes operate. Future applications should therefore incorporate multi-year monitoring, spatial analysis, and stronger policy linkages to enable the framework to be used not only as a diagnostic and comprehensive tool but also as a longitudinal monitoring and decision-support system. Moreover, the effective application of the HOLPA framework requires specialized training and technical capacity to generate meaningful and actionable insights.

While HOLPA provides a cross-sectional snapshot, the pronounced spatial heterogeneity across the transect can be interpreted as a potential surrogate for different stages along a transition pathway. For instance, the more diversified and higher-performing system in Kesra may represent a future state towards which more vulnerable, monoculture-dominated systems like Chouarnia could evolve. This interpretation suggests that the contextual factors and adherence patterns identified in Kesra (e.g., crop-livestock-tree integration, better market access) could serve as a model for sequencing interventions in less advanced communities. Future longitudinal monitoring is needed to validate this trajectory, but the spatial comparison offers valuable hypotheses for guiding adaptive management.

These results contribute to both national and international debates on the pathways, constraints, and governance of

agroecological transitions in semi-arid farming systems by highlighting the high path dependency shaped by historical land tenure and infrastructure disparities (Carpentier, 2025), suggesting that agroecological transitions in Tunisia unfold within deeply institutionalized trajectories rather than uniform adoption curves.

5 Conclusion

Agroecological transitions in semi-arid Tunisia unfold along highly context-dependent trajectories, where social values, cultural knowledge, and traditional practices provide resilient foundations, yet ecological functionality, climate mitigation, and participatory innovation remain underdeveloped. Resilience emerges not from diversification or biophysical conditions alone, but from the alignment of ecological design, adaptive knowledge, institutional support, and trust among local actors. The study demonstrates that HOLPA offers a flexible, multidimensional lens to identify critical entry points (such as soil restoration, livestock integration, and knowledge co-creation) for targeted, context-specific interventions. By coupling adherence diagnostics with performance outcomes, HOLPA enables the elaboration of contextualized roadmaps, highlighting windows of opportunity to scale locally adapted innovations while building trust and collaborative networks. Our findings yield three actionable priorities for policymakers and practitioners:

- Target Ecological Leverage Points: Redirect support towards practices with high biophysical impact and local feasibility, such as legumes integration...
- Institutionalize Knowledge Co-creation: Transition extension services to facilitate farmer-led experimentation and polycentric learning networks, directly engaging the documented social capital to bridge the gap in ecological practices.
- Strengthen Multi-Actor Governance: Develop integrated programs that connect the Ministry of Agriculture, local farmer organizations, and extension agencies to provide coherent support for diversification, veterinary services, and market access.

Nevertheless, HOLPA's household-level and static focus limits its capacity to capture temporal dynamics, landscape interactions, and policy feedback, underscoring the need for complementary monitoring tools and stronger integration with governance structures. While the household-level and static nature of HOLPA presents limitations for capturing landscape dynamics and long-term change, this diagnostic assessment establishes a critical baseline. Future work should employ longitudinal monitoring to validate transition pathways and integrate spatial analysis to scale insights from household to landscape levels. Ultimately, transforming local strengths into systemic change requires leveraging diagnostic tools like HOLPA to foster institutional coherence and co-design resilient, equitable agri-food systems.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

This research did not require Institutional Review Board (IRB) approval, as it involved non-interventional socio-economic research, including surveys and interviews with farmers, community leaders, and local agricultural administration officials. In Tunisia, such studies do not necessitate IRB approval, as they do not involve medical or clinical interventions, experiments on human subjects, or the collection of sensitive personal data. The study was conducted in accordance with the ethical standards of the National Institute of Agronomic Research of Tunisia (INRAT) and the Science for Resilient Livelihoods in Dry Areas (ICARDA). All participants were informed about the purpose of the study and participated voluntarily. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required from the participants or the participants' legal guardians/next of kin in accordance with the national legislation and institutional requirements because Written informed consent was not required for this study because participation was voluntary. The survey did not collect any personal sensitive data, and participants provided their consent by choosing to complete the questionnaire using KoboToolbox. This procedure is consistent with national legislation and institutional requirements in Tunisia for non-interventional socio-economic research.

Author contributions

WT: Investigation, Visualization, Data curation, Writing – original draft, Writing – review & editing, Conceptualization, Methodology, Formal analysis, Software. VA: Methodology, Validation, Supervision, Software, Resources, Project administration, Writing – original draft, Formal analysis. ZS: Data curation, Methodology, Formal analysis, Investigation, Writing – original draft. MB: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. HB: Supervision, Project administration, Resources, Writing – original draft, Validation, Methodology. LA: Validation, Project administration, Conceptualization, Supervision, Writing – original draft, Software. AW: Methodology, Project administration, Conceptualization, Writing – original draft, Investigation. ZI: Data curation, Resources, Writing – original draft, Investigation. QL: Resources, Project administration, Writing – original draft, Conceptualization, Methodology. UR: Resources, Funding acquisition, Writing – original draft, Project administration. HM: Resources, Writing – original draft, Validation, Funding acquisition, Investigation. MA: Validation, Supervision, Writing – original draft, Resources, Project administration. AF: Validation, Funding acquisition, Project administration, Supervision, Writing – original draft, Resources.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fagro.2026.1719829/full#supplementary-material>

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